PCT

WORLD INTELLECTUAL PR
Internation

INTERNATIONAL APPLICATION PUBLISHED UNL

WO 9607114A1

(51) International Patent Classification 6 : G02B 5/28

A1

(11) International Publication Number: WO 96/07114

(43) International Publication Date: 7 March 1996 (07.03.96)

(21) International Application Number: PCT/AU95/00551

(22) International Filing Date: 30 August 1995 (30.08.95)

(30) Priority Data:
PM 7746 30 August 1994 (30.08.94) AU

(71) Applicant *(for all designated States except US)*: PHOTONIC TECHNOLOGIES PTY. LTD. [AU/AU]; Suite 510, Eastgardens, 152 Bunnerong Road, Pagewood, NSW 2035 (AU).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: BETTS, Ralph, Alexander [AU/AU]; 39 Oberon Street, Randwick, NSW 2031 (AU). FRISKEN, Steven, James [AU/AU]; 43 Loch Maree Street, Maroubra, NSW 2035 (AU). WONG, Danny, Wai-Boown [AU/AU]; 12/44 Oberon Street, Randwick, NSW 2031 (AU).

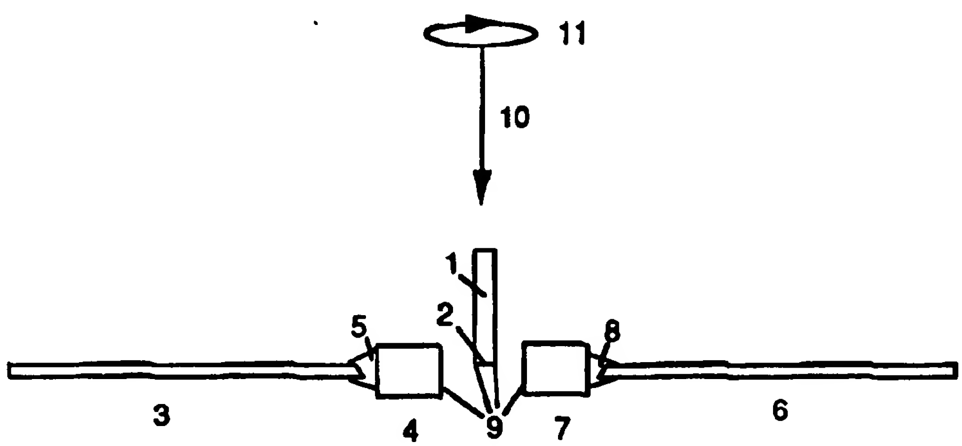
(74) Common Representative: BETTS, Ralph, Alexander; Photonic Technologies Pty. Ltd., Suite 510, Eastgardens, 152 Bunnerong Road, Pagewood, NSW 2035 (AU).

(81) Designated States: JP, US, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
With international search report.

(54) Title: SPLIT-BEAM FOURIER FILTER

(57) Abstract



An optical filter, comprising a first optical waveguide (3), a second optical waveguide (6) and means for expanding light from first optical waveguide into a beam (4), and at least one optical flat (1) inserted partially into the beam so that a fraction of the light passes through each optical flat (1) and a means for focussing the light into the second optical waveguide (7). In its simplest form the device has a Mach-Zehnder (sinusoidal) transmission characteristic. The filter can be tuned both in wavelength and extinction either mechanically or electrically. More complex (non-sinusoidal) characteristics can also be obtained. A number of implementations are disclosed.

FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AT	Austria	GB	United Kingdom	MR	Mauritania
AU	Australia	GE	Georgia	MW	Malawi
BB	Barbados	GN	Guinea	NE	Niger
BE	Belgium	GR	Greece	NL	Netherlands
BF	Burkina Faso	HU	Hungary	NO	Norway
BG	Bulgaria	IE	Ireland	NZ	New Zealand
BJ	Benin	IT	Italy	PL	Poland
BR	Brazil	JP	Japan	PT	Portugal
BY	Belarus	KE	Kenya	RO	Romania
CA	Canada	KG	Kyrgystan	RU	Russian Federation
CF	Central African Republic	KP	Democratic People's Republic of Korea	SD	Sudan
CG	Congo			SE	Sweden
CH	Switzerland	KR	Republic of Korea	SI	Slovenia
CI	Côte d'Ivoire	KZ	Kazakhstan	SK	Slovakia
CM	Cameroon	LI	Liechtenstein	SN	Senegal
CN	China	LK	Sri Lanka	TD	Chad
CS	Czechoslovakia	LU	Luxembourg	TG	Togo
CZ	Czech Republic	LV	Latvia	TJ	Tajikistan
DE	Germany	MC	Monaco	TT	Trinidad and Tobago
DK	Denmark	MD	Republic of Moldova	UA	Ukraine
ES	Spain	MG	Madagascar	US	United States of America
FI	Finland	ML	Mali	UZ	Uzbekistan
FR	France	MN	Mongolia	VN	Viet Nam
GA	Gabon				

Split-beam Fourier filter

Technical field

This invention relates to optical filtering, to means and methods for producing the filtering and to devices using such means and methods. In particular, this invention relates to optical filtering of light guided by optical waveguides such as optical fibre.

Background art

Many different types of filter have been demonstrated. These include various types of absorption filtering, dielectric single or multilayer filtering, interferometric filtering (Fabry-Perot, Michelson, Mach-Zehnder, Sagnac etc) and grating filtering.

A conventional (prior art) Mach-Zehnder filter consists of a beam splitter (or coupler) which splits the input light into two paths and a beam combiner (or coupler) to combine the light again. If the two paths have different lengths, the Mach-Zehnder filter has a wavelength dependent transmission characteristic.

The split-beam Fourier filter (SBFF) described in this document is a special type of filter which can give the same characteristic transmission as a Mach-Zehnder filter as well as more complex characteristics by simply splitting the beam of a fibre beam expander with an appropriate transparent element or elements so that different parts of the beam travel different optical path lengths. This gives highly stable performance and is ideally suited to incorporation in a single mode fibre beam expander.

Principle of Operation

The split-beam Fourier filter consists of a number of plates of glass appropriately positioned in a fibre beam expander. In the case of one plate of glass (single element) in one beam expander (single stage), the wavelength characteristic is that of a Mach-Zehnder filter - sinusoidal with a wavelength period dependent on the thickness of the glass plate. Excellent loss and extinction have been obtained, and mechanical tuning of the characteristic (both wavelength and extinction) is straightforward. The use of multiple elements allows more complex filter characteristics.

Figure 1 shows the elements comprising a single stage split-beam Fourier filter. The filter is a flat plate of glass (1) with one edge (2) carefully polished perpendicular to the plate surface -

this edge splits the beam of a fibre beam expander. Light passing through the plate will experience a wavelength dependent phase shift compared with the light that does not pass through the plate. If the phase shift is zero or a multiple of 2π, then the beam is unchanged and the transmission is maximum (100%). If the phase shift is π, then the E field is inverted in one half of the beam compared to the other, giving an antisymmetric E field distribution in the beam. The result at the output fibre tip is an E field distribution which is the two dimensional Fourier transform of the beam E field which is also an antisymmetric function. The overlap of this distribution with the fundamental fibre mode is zero therefore no light will be launched into the fibre if the fibre is single mode. Analysis shows that the transmission, T is given by:

$$T = 1 - s\sin^2(\Delta\phi / 2) \qquad (1)$$

where $\Delta\phi = 2\pi(n-1)L/\lambda$ is the phase difference, n is the refractive index and L is the thickness of the glass plate, λ is the wavelength and s is the suppression of extinction which depends on the fraction of the beam passing through the plate (when the plate exactly bisects the beam, s=1).

Brief description of the drawings

Figure 1 is a schematic view of a single element, single stage, split-beam Fourier filter.

Figure 2 shows the transmission characteristic of a split-beam Fourier filter with various extinctions and centre wavelengths.

Figure 3 shows the location of two plates (viewed along beam) to give a combined characteristic.

Figure 4 shows the extension to 4 plates.

Figure 5 shows an alternative plate distribution to achieve complex filtering characteristics.

Figure 6 shows the two dimensional version of figure 5.

Figure 7 shows the construction of an electrically tunable phase plate.

Figure 8 shows a switchable split-beam Fourier filter.

Figure 9 shows a split-beam mode convertor.

Figure 10 shows an optical amplifier incorporating a split-beam Fourier filter for gain flattening.

Figure 11 shows the saturated gain characteristic of an Erbium doped fibre amplifier with and without a split-beam Fourier filter

Detailed description

Figure 1 shows the elements comprising one embodiment of a single stage split-beam Fourier filter. The filter is a flat plate of glass (1) with one edge (2) carefully polished perpendicular to the plate surface - this edge splits the beam of a fibre beam expander consisting of a first fibre (3) glued to a lens (4) with transparent glue (5) and a second fibre (6), lens (7) and glue (8). Anti-reflection coatings (9) on the lenses and plate improve transmission and suppress cavity resonances.

Light passing through the plate experiences a wavelength dependent phase shift compared with the light that does not pass through the plate. If the phase shift is zero or a multiple of 2π, then the beam is unchanged and the transmission is maximum (100%). If the phase shift is π, then the electric field (E field) is inverted in one half of the beam compared to the other, giving an antisymmetric E field distribution in the beam. The result at the output fibre tip is an E field distribution which is the two dimensional Fourier transform of the beam E field which is also an antisymmetric function. The overlap of this distribution with the fundamental fibre mode is zero therefore no light will be launched into the fibre if the fibre is single mode. Since the phase shift is wavelength dependent, the device transmission is wavelength dependent.

A filter of this type was constructed using a fibre beam expander and a 92μm thick optically flat plate of glass which was edge polished and mounted on a positioner allowing insertion into the beam in the direction of the arrow (10) and rotation about this axis (11). A maximum extinction greater than 35dB and a transmission loss of 0.20dB were observed (using a 1mm beam diameter). The wavelength period was 54nm. Tuning through more than a complete wavelength period was accomplished by tilting the plate about the arrowed axis (10) with negligible increase in loss. Polarisation dependence was measured to be less than 0.1dB.

Figure 2 shows the transmission characteristic of a split-beam Fourier filter with various extinctions and centre wavelengths. All characteristics have a free spectral range (FSR) of

32nm. The characteristic labelled (32) gives 100% extinction at 1550nm, the characteristic labelled (33) gives 40% extinction at 1550nm and the characteristic labelled (34) gives 70% extinction at 1564nm.

Figure 3 shows the location of two plates (12) (viewed along beam (13)) to give a combined characteristic.

Figure 4 shows the extension to 4 plates (14).

Figure 5 shows an alternative plate distribution to achieve complex filtering characteristics.

Figure 6 shows the two dimensional version of figure 5.

Figure 7 shows the construction of an electrically tunable phase plate. Many means exist for moving the plate in response to an electrical signal (electric stepper motors, piezo-electric positioners etc). In some cases it is more desirable is to fix the element and to achieve electrical tuning without movement. This can be achieved by varying the optical path length of one or both sides of the element in the beam via the electro-optic effect if the element is electro-optic.

For typical electro-optic crystals, this requires a large voltage, however if liquid crystal films are used, a large change in the optical path can be achieved for a moderate voltage (<10V). Figure 7 shows a preferred embodiment using two thin layers of liquid crystal (15) to achieve polarisation independent operation. The glass plates (16) are coated with a transparent conducting material (17) (eg Indium Tin Oxide, ITO) and separated by spacers (18) typically 10μm in thickness. The conducting material is treated such that for no applied field, the liquid crystal in layer 1 aligns along the x axis and in layer 2 aligns along the y axis. Application of an electric field causes the liquid crystal in both layers to align along the z axis resulting in a polarisation independent change in optical path travelled by the beam (19). At an appropriate operating point, the optical path or phase change will be close to linearly dependent on applied voltage.

Figure 8 shows a single element switchable split-beam Fourier filter. The construction is similar to a standard SBFF but the element (optical flat) (20) can be switched electro-mechanically or otherwise from a position out of the beam (21) to a position in the beam (22), as indicated by the arrow, which gives the required filter characteristics.,

Figure 9 shows a split-beam mode convertor - the only difference from the SBFF described above being that the fibres (23, 24) support two or more optical modes and the element

approximately bisects the beam. If fibre which supports two modes (LP_{01} and LP_{11}) is used rather than single mode fibre, an SBFF can be effectively used as a mode convertor (converting power in the LP_{01} mode of the input fibre (23) to power in the LP_{11} mode of the output fibre (24) and vice versa when light enters the device from the opposite direction).

Figure 10 shows an optical amplifier (28) incorporating a split-beam Fourier filter (29) at the output for gain flattening. The filter can be incorporated at the input or at an intermediate stage within the amplifier.

Figure 11 shows the saturated gain characteristic of an Erbium doped fibre amplifier with (30) and without (31) a split-beam Fourier filter.

Applications

Numerous applications for optical filters exist, and the SBFF is eminently suitable for all fibre applications where a Mach-Zehnder transmission characteristic is required. The following sections describe a number of applications for which the SBFF is ideally suited. This list is however by no means exhaustive.

- **Filtering:** All fibre applications where a Mach-Zehnder transmission characteristic is required.

- **Gain flattening in Erbium doped fibre amplifiers (EDFAs):** An SBFF in series with an EDFA can give an appropriate characteristic for flattening the gain of the EDFA (which is important in wavelength division multiplexed multiamplifier systems) as described above.

- **Notch filter in EDFA:** The SBFF can be used as a notch filter in a two stage EDFA to attenuate the 1533nm ASE peak. This gives a greater gain bandwidth product over the entire gain bandwidth of the EDFA and lower noise figure without compromising gain.

- **Mode convertor:** If fibre which supports two modes (LP01 and LP11) is used rather than single mode fibre, an SBFF can be effectively used as a mode convertor (converting power in the LP11 mode of the input fibre to power in the LP11 mode of the output fibre and vice versa).

This can be used for a number of applications including:

spatial separation with modal coupler - this is a 3 port device - the transmission from port 1 to port 2 is simply that of the standard SBFF, but the normally rejected power is now routed to port 3 by virtue of the LP11 mode being coupled across to port 3.

dispersion compensation using LP11 mode - it has been proposed and demonstrated [1] that if power is carried in the LP11 mode of a two mode fibre, a large and negative dispersion parameter, D can be achieved suitable for compensating the dispersion of standard single mode fibre when used at 1550nm wavelength. The SBFF is an ideal device for efficiently converting power from the fundamental mode (LP01) of a single mode input fibre to the LP11 mode of a two mode output fibre. It is also ideal for converting this power back to the fundamental mode of a single mode fibre after compensation.

- **Sliding / guiding filter:** Filters with a cyclic wavelength characteristic have been proposed and demonstrated [2] for long distance multiamplifier transmission of solitons. In these demonstrations, low extinction Fabry-Perot filters were used. The SBFF offers a simpler alternative with improved loss and characteristic control.

- **Transversal / lattice filter for dispersion compensation and signal processing:** Cascaded Mach-Zehnder filters have been proposed and demonstrated for optical signal processing including dispersion compensation [3]. In these demonstrations, an integrated silica waveguide implementation was used. A multiple element SBFF potentially offers greater control and better performance for such devices.

- **Attenuator:** A polarisation independent attenuator can be produced using an SBFF. The centre wavelength of attenuation is the extinction wavelength. The device can be made broadband by using an element which shifts the phase between the two halves by π - this gives a 30dB bandwidth at about 1% of centre wavelength. Further increases in bandwidth can be achieved using multiple similar elements.

- **Tunable polarisation dependent attenuator:** A tunable polarisation dependent attenuator can be produced using an SBFF in which the optical flat is a half wave plate. In this case when the centre wavelength (wavelength of maximum extinction) of the Mach-Zehnder for light polarised along one axis of the half wave plate is tuned to approximately equal the centre wavelength of the half wave plate, then insertion of this element into the beam attenuates only this polarisation. Such devices can be used for compensating polarisation dependent loss or introducing polarisation dependent loss in optical transmission systems.

Although a number of embodiments have been described in relation to the present invention, it will be apparent to those skilled in the art that the concept of the invention could be applied in various other ways in other embodiments.

References

[1] C D Poole et al "Elliptical core dual mode fibre dispersion compensator" IEEE Phot. Tech. Lett., 5, pp194-197 (1993)

[2] L F Mollenauer et al "Demonstration, using sliding-frequency guiding filters, of error free soliton transmission over more than 20,000km at 10Gbit/s ..." in Conf. on Opt. Fiber Comm. 1993 (OSA, Wasahington DC. 1994) paper PD8, pp37-40

[3] M Kawachi, K Jinguji "Planar lightwave circuits for optical signal processing" in Conf. on Opt. Fiber Comm. 1994 (OSA, Wasahington DC. 1994) pp281-282

Claims

1. An optical filter, comprising a first optical waveguide, a second optical waveguide and means for expanding light from first optical waveguide into a beam, and at least one optical flat inserted partially into the beam so that a fraction of the light passes through each optical flat and a means for focussing the light into the second optical waveguide.

2. An optical filter as claimed in claim 1 in which input and output waveguides comprise single mode optical fibres.

3. An optical filter, as claimed in any preceding claim, in which the means for expanding and the means for focussing comprise gradient index lenses.

4. An optical filter, as claimed in any preceding claim, in which the means for focussing is the means for expanding and an optical reflector is used to allow the beam to pass twice through said means.

5. An optical filter, as claimed in claim 4, where first waveguide and second waveguide are parallel waveguides.

6. An optical filter, as claimed in any preceding claim, where the first waveguide is the second optical waveguide and the second waveguide is the first waveguide.

7. An optical filter, as claimed in any preceding claim, in which the optical waveguide is terminated at a non-perpendicular angle and the fibre is offset slightly from the centre of the lens system to reduce backreflection.

8. An optical filter, as claimed in any preceding claim, in which the optical flat comprises a 30 μm to 1000μm thick polished glass flat, with one edge polished or cleaved approximately perpendicular to the faces, providing the interface between light which passes through the flat and light which doesn't pass throught the flat.

9. An optical filter, as claimed in any preceding claim, in which the optical flat is antireflection coated to reduce Fabry-Perot resonances

10. An optical filter, as claimed in any preceding claim, in which tuning is achieved by varying the angle of one or more plates and / or the lateral displacement of one or more plates.

11. An optical filter, as claimed in any preceding claim, in which the tuning of the wavelength is varied by using a slightly wedged or stepped optical element and varying its position in the beam independently of its lateral displacement into the beam

12. An optical filter, as claimed in any preceding claim, in which the tuning is fixed at time of manufacture by setting the angle and position of the optical flat in the beam.

13. An optical filter, as claimed in any preceding claim, providing decreased temperature sensitivity by use of a material for the flat which has a negative refractive index coefficient with respect to temperature and a positive expansion coefficient with respect to temperature.

14. An optical filter, as claimed in any preceding claim, in which a non sinusoidal filtering function is achieved by use of two optical flats with approximately parallel interfaces.

15. An optical filter, as claimed in any preceding claim in which one or more of the optical flats are can be moved into its or their positions resulting in a switchable filter.

16. An optical filter as claimed in any preceding claim where tuning is achieved by varying the optical path through the element or elements using appropriate electro-optic or magneto-optic materials and varying electric or magnetic fields respectively.

17. A mode convertor comprising a first optical waveguide, a second optical waveguide and means for expanding light from first optical waveguide into a beam, and at least one optical flat inserted partially into the beam so that a fraction of the light passes through each optical flat and a means for focussing the light into the second optical waveguide. In this case the optical waveguides must support more than one mode.

18. A mode convertor as claimed in claim 17 in which the first optical waveguide is single mode and the second optical waveguide supports only the first two optical modes and only one optical flat is used which approximately bisects the beam. This device converts power carried in the fundamental mode of the first waveguide to power in the first higher order mode of the second waveguide and vice versa when used in the opposite direction.

19. An optical attenuator comprising a split-beam Fourier filter as claimed in claim 1, utilising the attenuation at the centre wavelength introduced by the filter.

20. An optical attenuator as claimed in claim 19 in which the deveice is made to operate over a broad ba:.d by using an optical flat with a step which introduces a phase change of π radians.

21. A device giving variable polarisation dependent loss comprising a first optical waveguide, a second optical waveguide and means for expanding light from first optical waveguide into a beam, and at least one half wave plate inserted partially into the beam so that a fraction of the light passes through each optical flat and a means for focussing the light into the second optical waveguide.

22. An optical amplifer including a split-beam Fourier filter at input, output or mid-stage for gain flattening or gain equalisation.

23. An optical amplifier as claimed in claim 22 in which the optical amplifier is an Erbium doped fibre amplifier or a Praseodymium doped fibre amplifier.

24. An optical amplifier as claimed in claim 23 in which the split beam Fourier filter is switchable so that the amplifier can be switched from being optimised for gain flatness to being optimised for output power.

Drawings

Figure 1

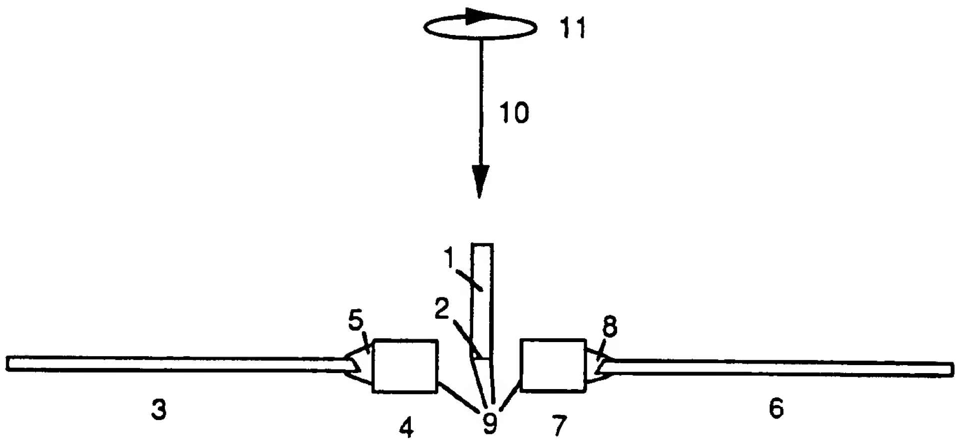


Figure 2

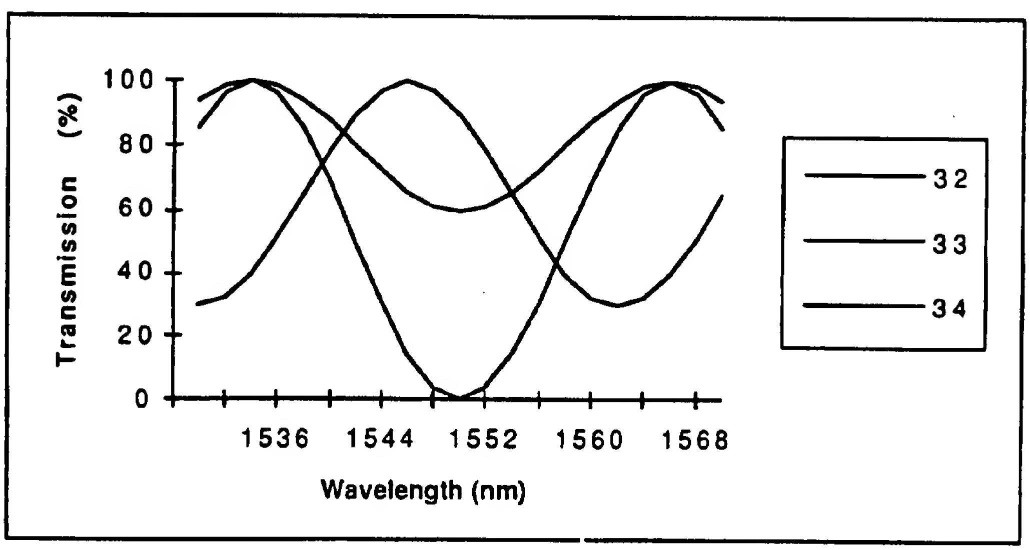


Figure 3

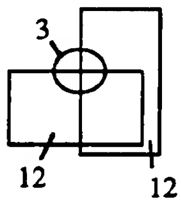


Figure 4

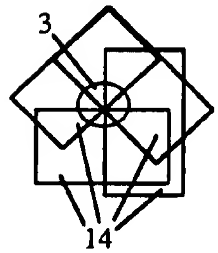


Figure 5

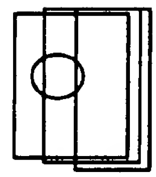


Figure 6

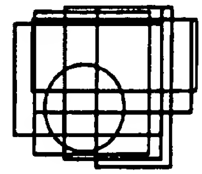


Figure 7

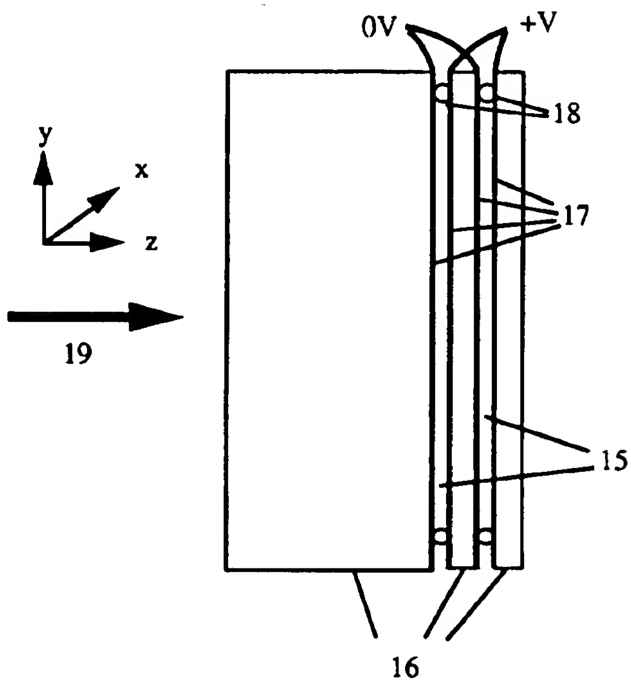


Figure 8

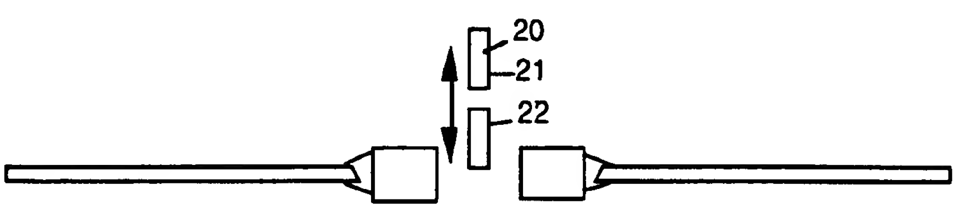


Figure 9

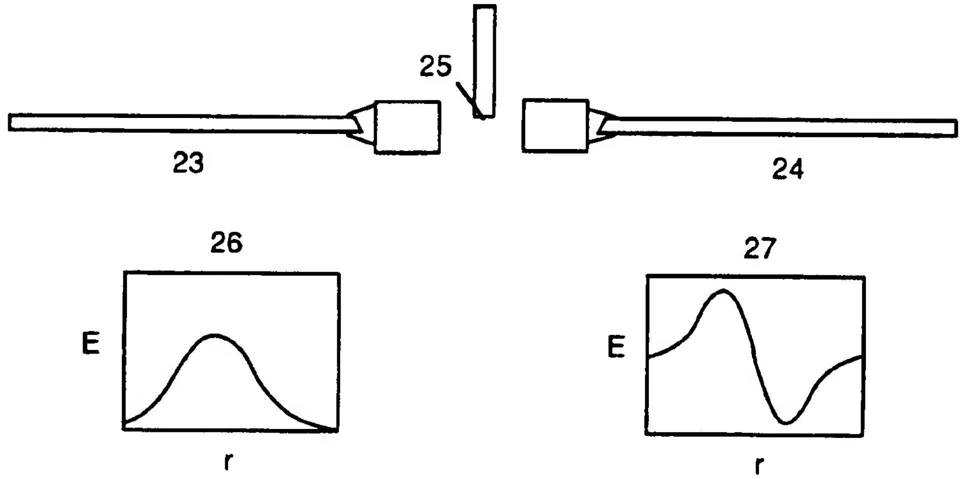


Figure 10

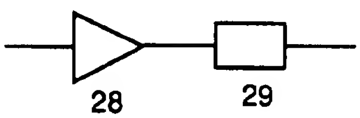
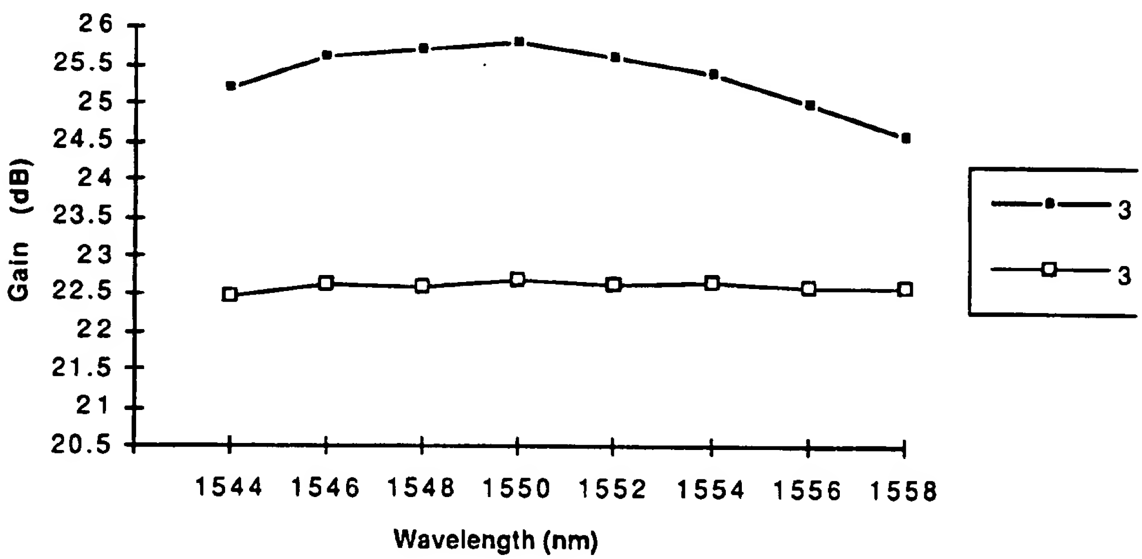


Figure 11



INTERNATIONAL SEARCH REPORT

International Application No.
PCT/AU 95/00551

A.	CLASSIFICATION OF SUBJECT MATTER

Int Cl[6]: G02B 5/28

According to International Patent Classification (IPC) or to both national classification and IPC

B.	FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC: G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
AU: IPC as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
DERWENT: G02B AND (WAVEGUIDE# OR FIBER# OR FIBRE#) AND (FOCUS: OR LENS:)
JAPIO: AND (OPTICAL FLAT# OR HALF()WAVE PLATE# OR HALFWAVE PLATE#)

C.	DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	AU 75178/91 A (AUSTRALIAN TELECOMMUNICATIONS CORPORATION) 3 October 1991 Figure 1	
A	EP 74144 A1 (N.V. PHILIPS GLOEILAMPENFABRIEKEN) 16 March 1983 Figures 1 and 2.	
A	EP 98730 A2 (FUJITSU LIMITED) 18 January 1984 Figures 5A-5C	

[X] Further documents are listed in the continuation of Box C   [X] See patent family annex

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier document but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
14 November 1995	4.12.95
Name and mailing address of the ISA/AU AUSTRALIAN INDUSTRIAL PROPERTY ORGANISATION PO BOX 200 WODEN ACT 2606 AUSTRALIA Facsimile No.: (06) 285 3929	Authorized officer Derek Barnes Telephone No.: (06) 283 2198

C (Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 343489 A2(OKI ELECTRIC INDUSTRY COMPANY LIMITED) 29 November 1989 Figure 3	

INTERNATIONAL SEARCH REPORT

International Application No.
PCT/AU 95/00551

Information on patent family members

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member					
EP	74144	CA	1180095	JP	58054322	NL	8104122
		US	4852962				
EP	98730	CA	1253726	JP	59002016	US	4712880
		JP	59002010				
EP	343489	AU	34954/89	JP	1292875	US	4995696
							END OF ANNEX